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Inline Modeling of Cross-Beam Energy Transfer and Stimulated Raman Scattering in Radiation- Hydrodynamics Codes

D. J. Strozzi, S. M. Sepke, G. D. Kerbel, D. S. Bailey, P. Michel, L. Divol, C. Thomas

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Inline Modeling of Cross-Beam Energy Transfer and Stimulated Raman Scattering in Radiation-Hydrodynamics Codes

Anomalous Absorption Meeting
15 June 2015

D. J. Strozzi, S. M. Sepke, G. D. Kerbel,
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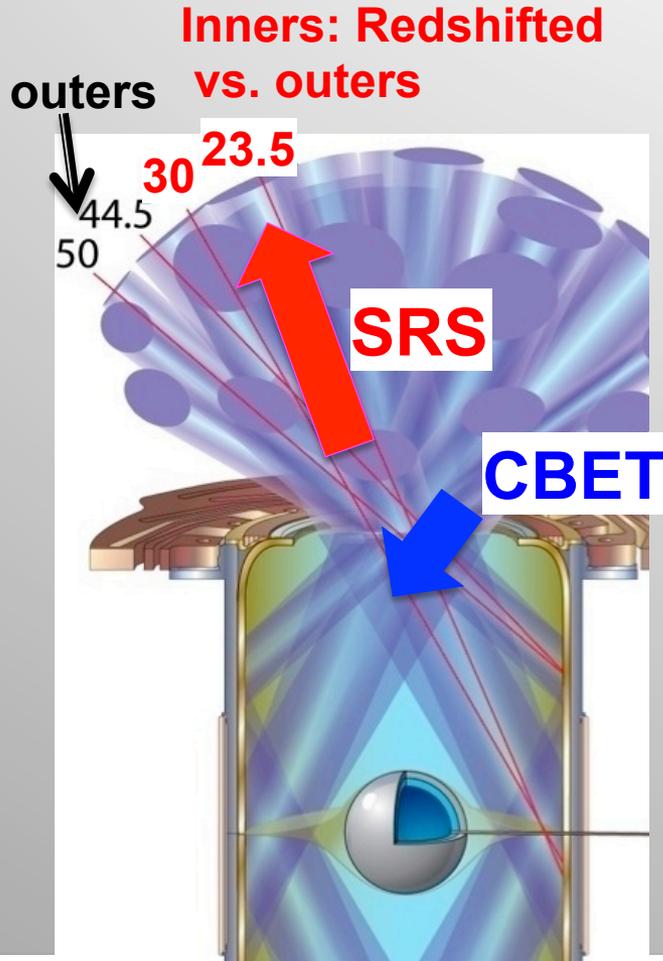
 Lawrence Livermore
National Laboratory



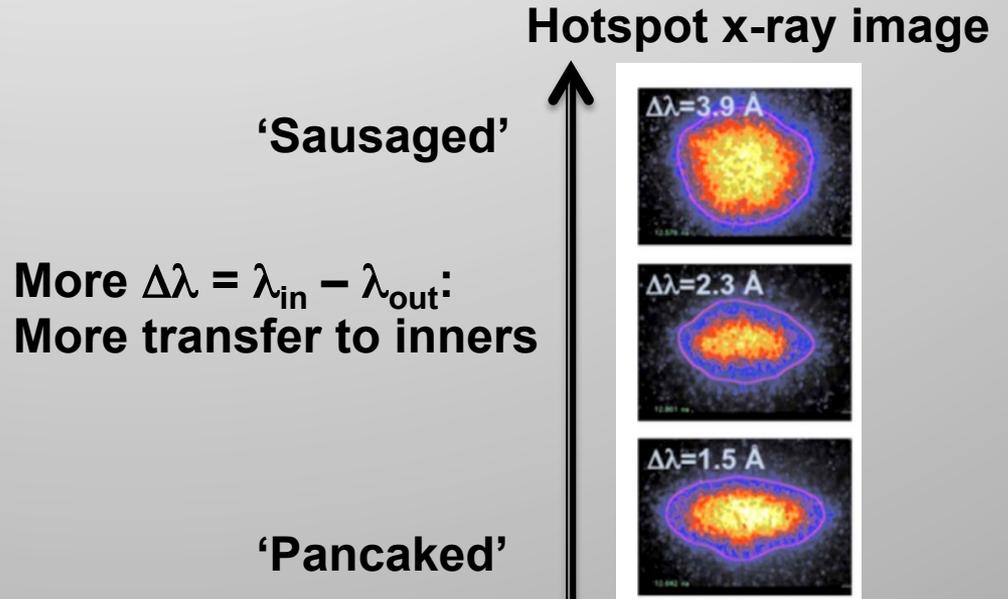
LLNL-CONF-673295

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

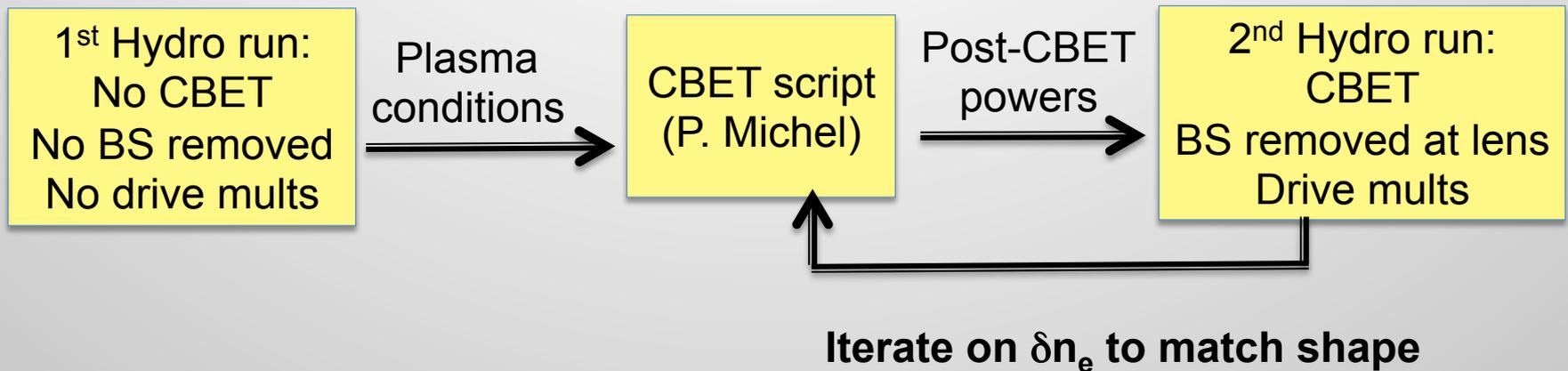
Cross-beam energy transfer (CBET) to inners used on NIF to control shape for hohlraum gas fill $\geq 0.96 \text{ mg/cm}^3$



- Low- and high-foot designs
- Transfer from “pump” to “probe” beam with lower frequency in plasma frame
- 3 NIF wavelengths (“colors”): 23°, 30°, outers
- Stimulated Raman scattering (SRS):
Laser photon \rightarrow scattered photon + Langmuir wave



Current two-run “Script Process”: CBET must be limited to match shape data



“The Shape Problem:”

- More CBET to inners than matches shape data
- $\delta n_e/n_e$ clamp on ion wave amplitude to limit CBET
- Labor intensive
- Not predictive

Inline models of CBET and SRS have been added to rad-hydro codes Hydra and Lasnex

Inline model: rad-hydro code calculates LPI every time step

Advantages vs. script process:

- One run, not two
- More CBET physics:
 - Refraction, inverse brems., spatially non-uniform transfer
 - Ion wave energy deposition – affects LEH temperature
- More SRS physics:
 - Pump depleted in target
 - SRS light grows in target
 - Langmuir-wave and SRS inverse brems. heating

Summary: Inline models of CBET and SRS are moving toward accurate modeling of implosion shape

Inline CBET in Hydra

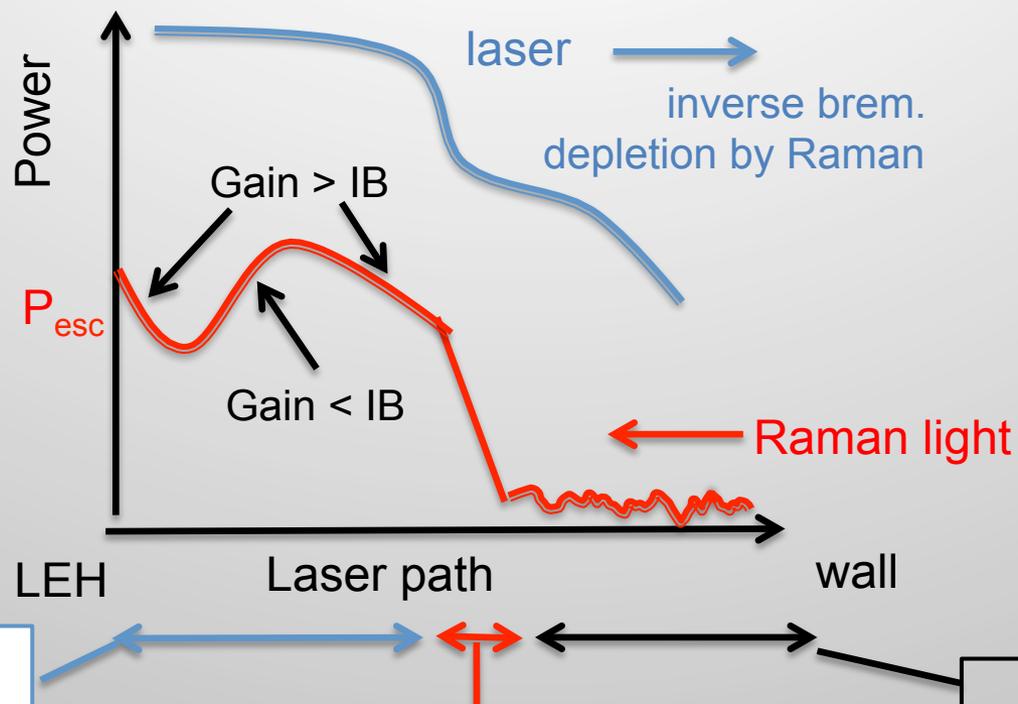
- No known bugs – hats off to Scott Sepke!
- Inline CBET less than script in picket, almost as much in peak power
- See D. J. Strozzi, Anomalous 2014, APS-DPP 2014 – or discuss in person

Inline CBET and SRS in Lasnex: applied to early high-foot NIF symcap

Two runs with inline CBET:

- Run A: SRS removed “at lens” = from incident laser
- Run B: inline SRS
 - SRS light grows as it propagates to LEH – gain exceeds inverse brems.
- Inline SRS vs. lens SRS:
 - LEH hotter – affects CBET
 - DRIVE: total x-ray drive and energetics same
 - SHAPE: x-ray drive stronger on pole → pancaked shape
 - Closer to data with larger δn_e clamp

SRS physical picture: resonant growth from noise, post-resonant growth and absorption



Post-resonance

- Non-resonant growth, inv. brems.
- 1D linear gain should suffice

Resonance

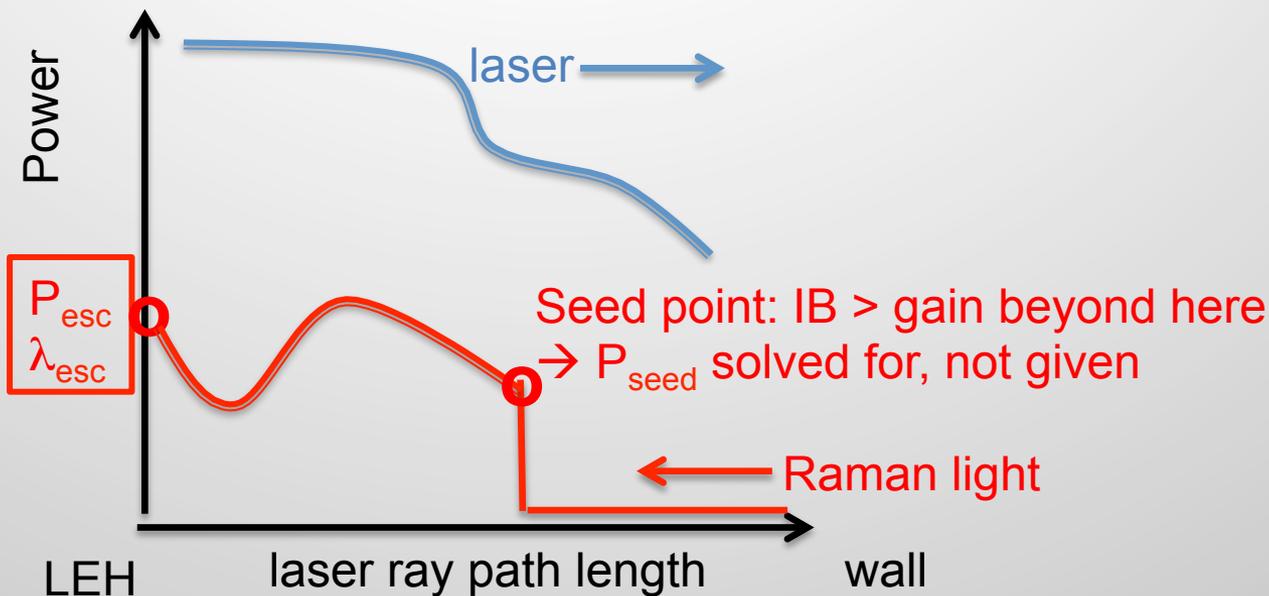
- Raman grows from noise to finite level
- Length \sim speckle length
- Most exponentiation
- One $\{n_e, T_e\} \rightarrow$ Raman wavelength
- "Fun physics:" speckles, kinetics, pF3D, PIC

Pre-resonance

Thermal Raman noise: brems., Thomson

Inline SRS model: 1D coupled-mode equations in post-resonant region

User gives SRS power, wavelength



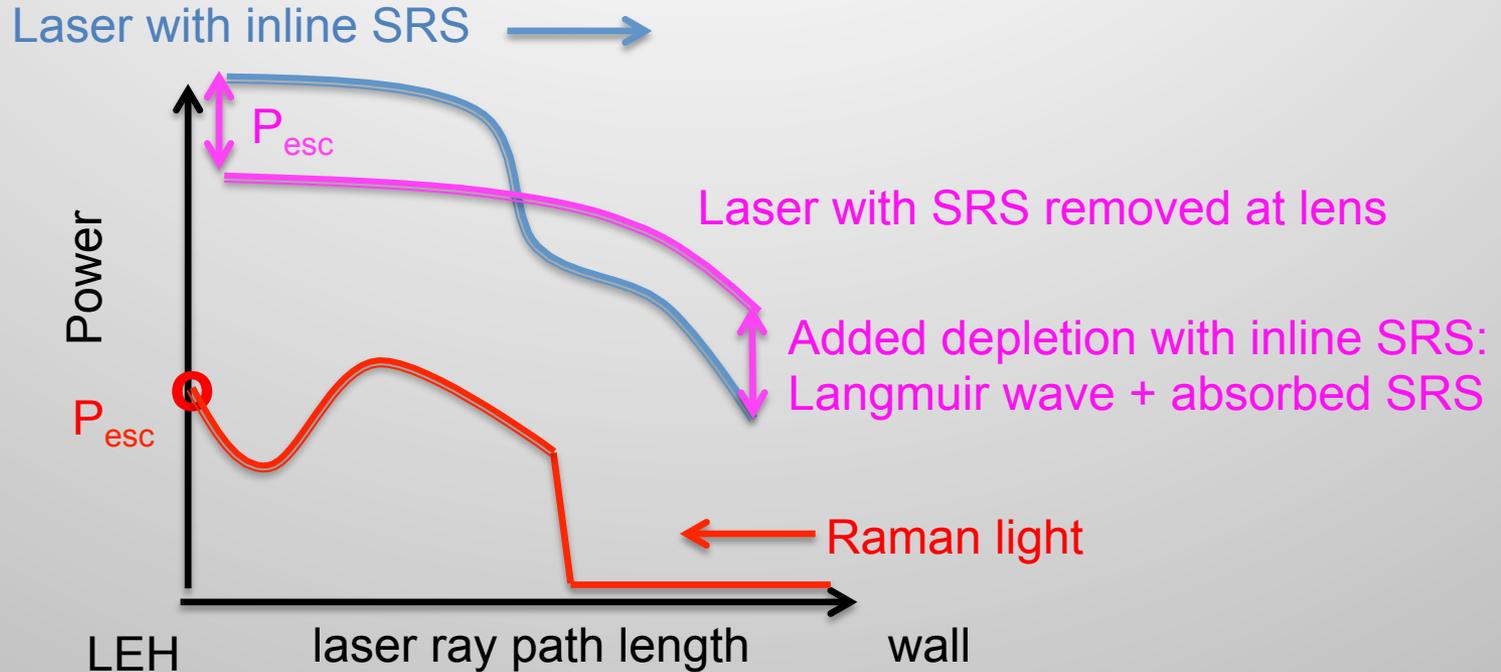
Post-resonance
 1D plane-wave coupled-mode equations solved until turning point reached

Resonance
 $P_{SRS} = P_{seed} = \text{finite seed power}$

Pre-resonance
 $P_{SRS} = 0$

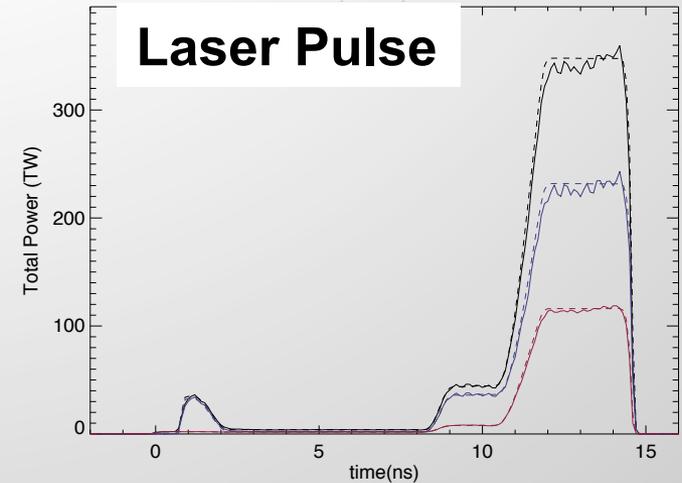
$$\begin{aligned} \partial_z I_0 &= -\kappa_0 I_0 - \omega_0 K I_0 I_1 && \text{pump laser} \\ -\partial_z I_1 &= -\kappa_1 I_1 + \omega_1 K I_0 I_1 && \text{scattered light} \\ p_{EPW} &= (\omega_0 - \omega_1) K I_0 I_1 && \text{Langmuir wave power} \end{aligned}$$

Inline SRS has more pump depletion than SRS removed at lens

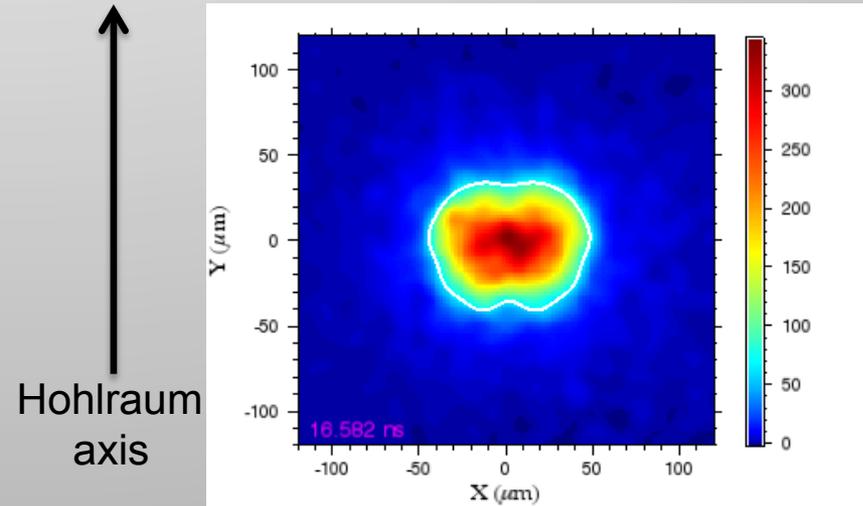


NIF shot N121130: early high-foot symcap

- Laser
 - $E_{\text{laser}} = 1274 \text{ kJ}$ $P_{\text{laser}} = 350 \text{ TW}$
 - $(\lambda_{23}, \lambda_{30}) - \lambda_{\text{out}} = (8.5, 7.3) \text{ Ang.}$
 - Large CBET to inners: tune P2 shape
 - “3-color” CBET to 23’s: tune azimuthal M4 shape
- Hohlraum: Au, “575 size”
 - Fill: 1.45 mg/cc He, current high-foot 1.6 mg/cc
- Capsule: CH, D-He3 gas fill – no DT layer
- Results
 - ~16% laser energy backscattered
 - Mostly inner SRS
 - Bangtime: 16.6 ns
 - Hotspot pancaked: pole-high x-ray drive



**Hotspot x-ray image at bangtime:
“Pancaked”, $P_2/P_0 = -0.12$**

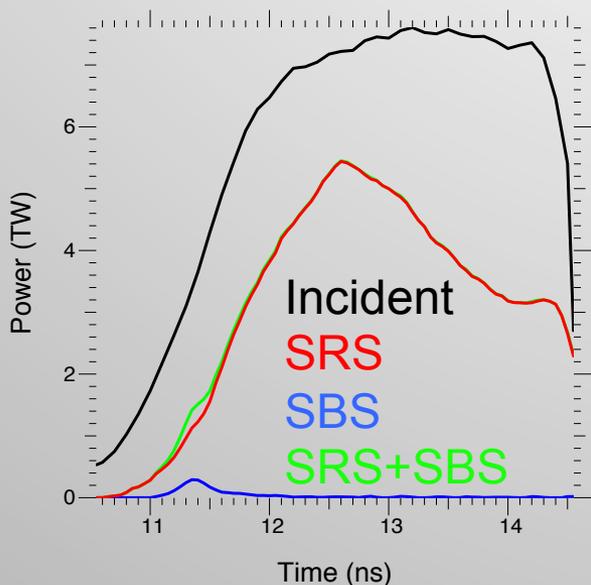


Inline SRS: user specifies power and wavelength of escaping SRS light

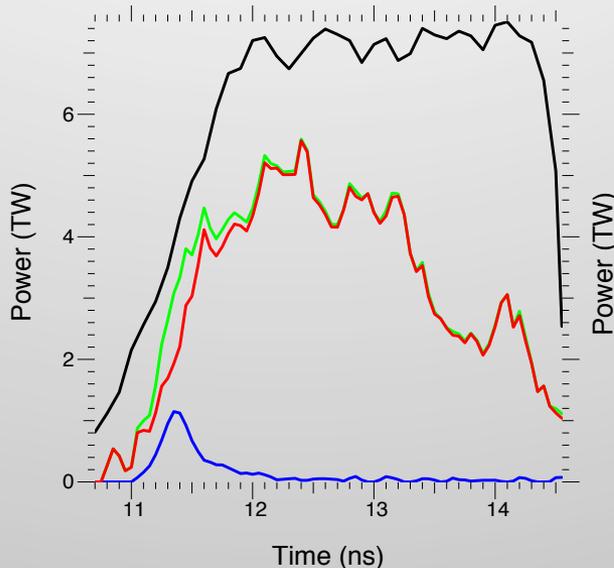
NIF shot N121130

Inner cones

Q31B: cone 30

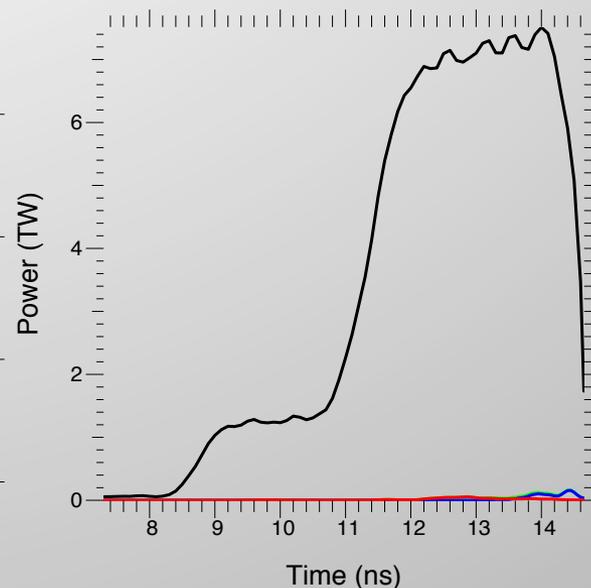


Q33B: cone 23



Outer cone

Q36B: cone 50

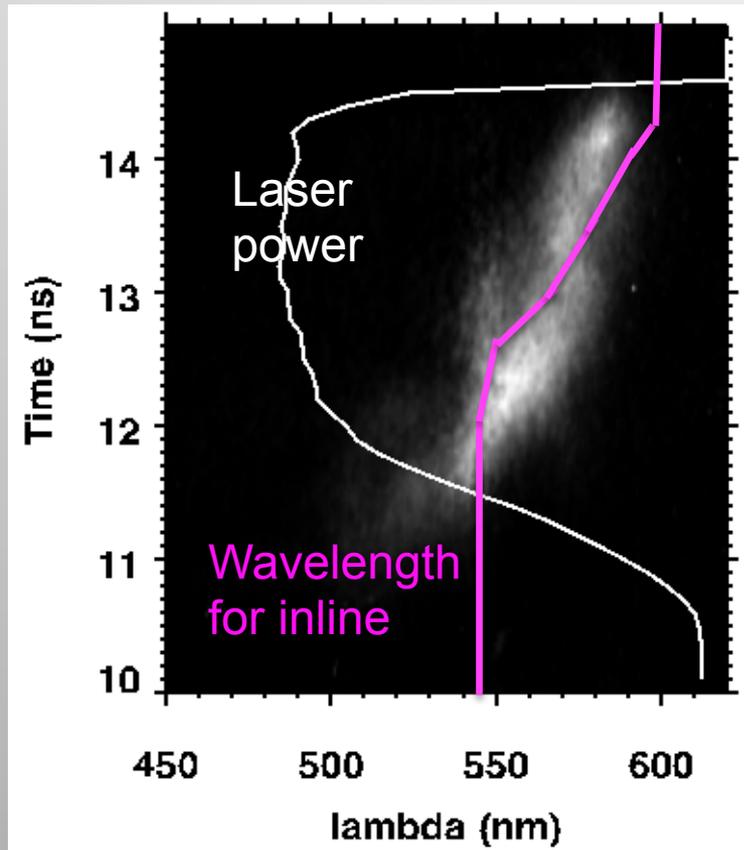


Inline SRS: user specifies power and wavelength of escaping SRS light

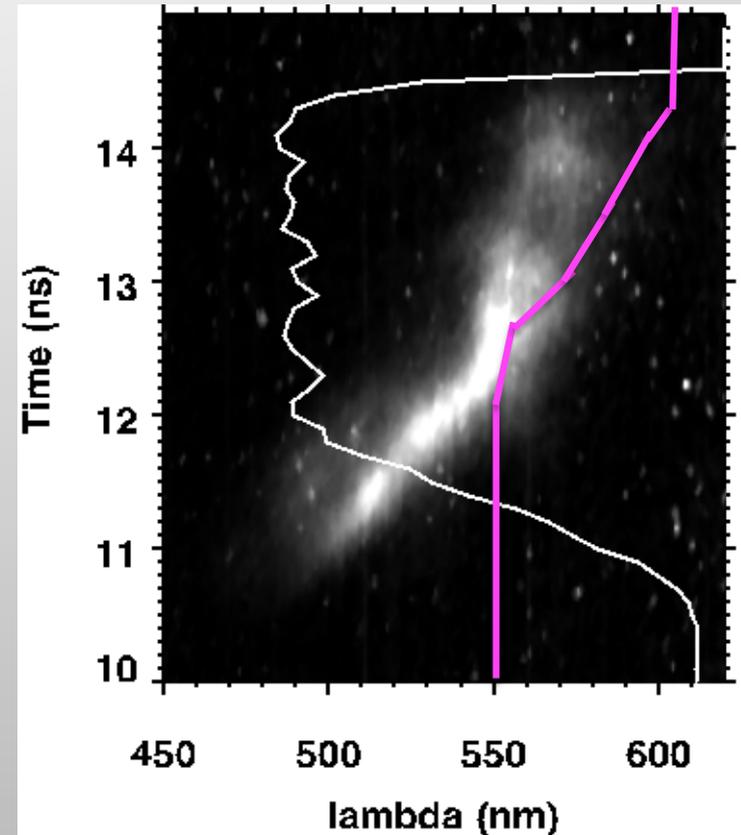
NIF shot N121130

Chose wavelength close to cone 30 measured value, used same for cone 23

SRS – cone 30



SRS – cone 23



Lasnex inline CBET and SRS modeling of N121130

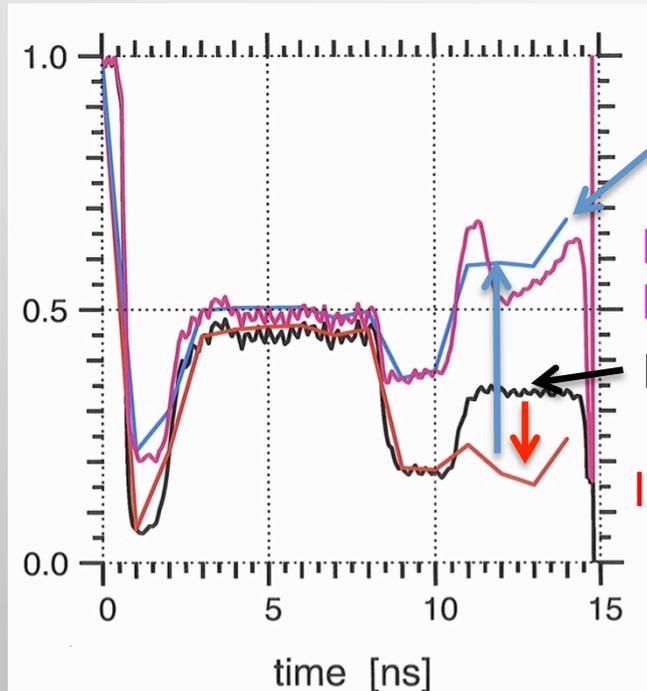
Three runs by C. Thomas, all with:

- Lagrange mesh management: better match x-ray and capsule drive data
- High-flux model: DCA opacities, $f=0.15$ flux limit
- CBET saturation clamp $\delta n_e/n_e = 10^{-3}$

- Run A: Traditional two-step “CBET script process”
- Run B: Lens SRS + Inline CBET
- Run C: Inline SRS + Inline CBET

Lasnex inline SRS and lens SRS give similar cone fraction – neglecting Langmuir-wave heating

Cone fraction =
Inner / total power



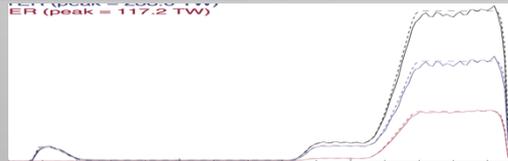
Lens-SRS:
Incident – escaping SRS + CBET

Inline-SRS:
Incident – escaping SRS + CBET

Full incident laser

Incident – escaping SRS

Laser
Pulse



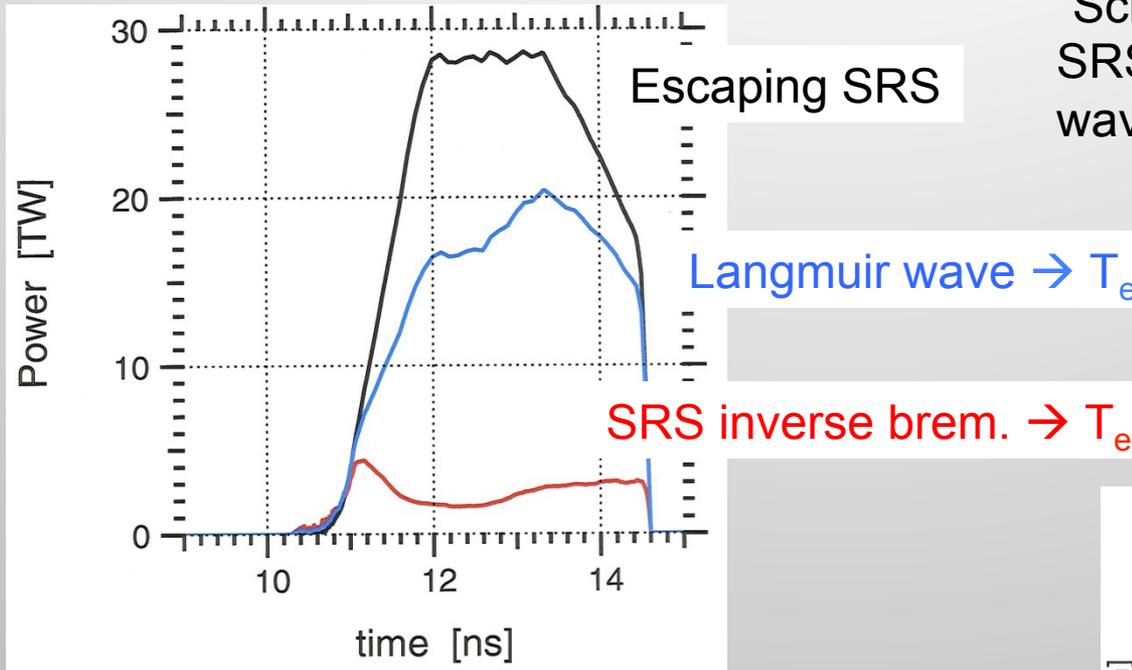
Inline SRS

- Langmuir-wave heating, SRS inv. brems. further deplete inner beam at wall
- Reduces equatorial x-ray drive on capsule

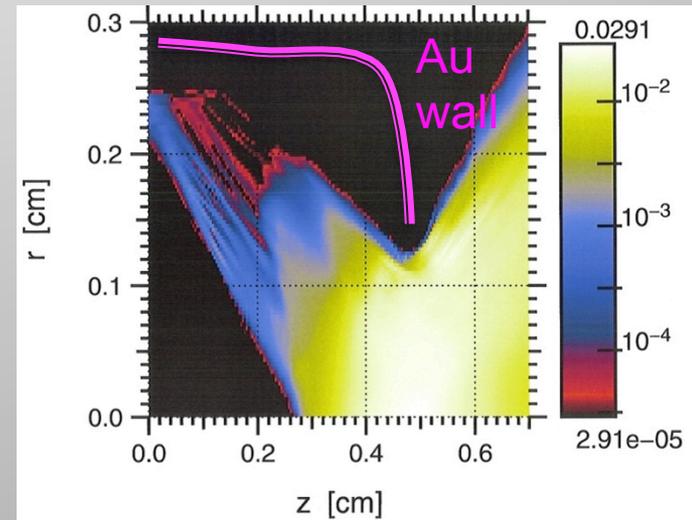
Lasnex inline SRS energetics: inverse brems. of SRS light not energetically significant

Inner cone SRS: 23's + 30's

“Script” process and removing SRS at lens neglect Langmuir wave and SRS IB heating



SRS light intensity [a.u.]



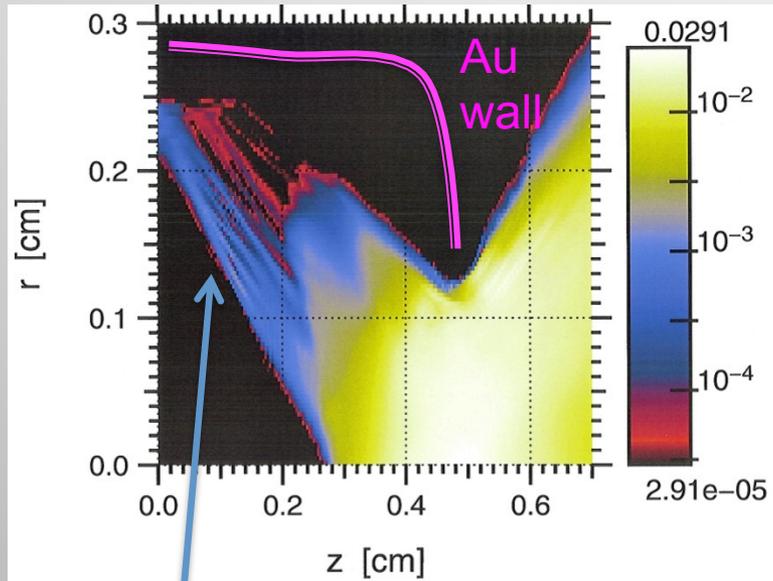
Manley-Rowe for Langmuir waves:

$$P_{Langmuir} = \frac{\omega_{las} - \omega_{srs}}{\omega_{srs}} * [P_{srs}^{esc} + P_{srs}^{IB}]$$

Inline SRS: gain exceeds absorption as it propagates, most heating just inside LEH

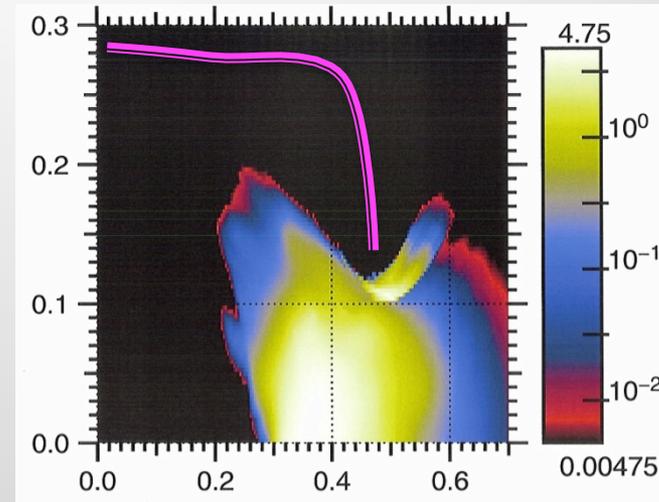
t = 13 ns

SRS light intensity [a.u.]

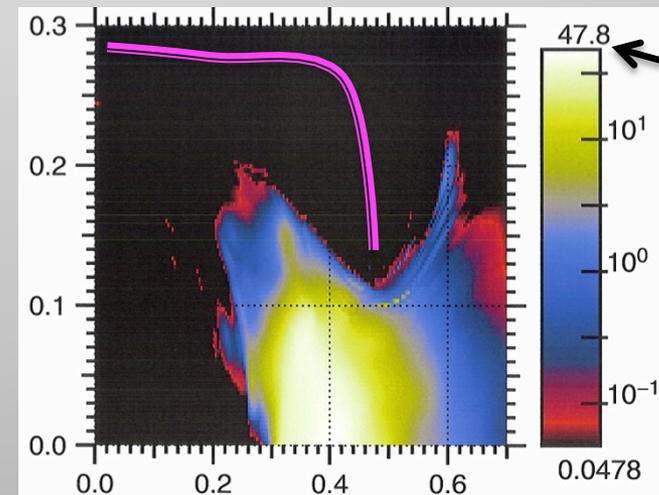


* Small azimuthal volume with high intensity: little power

SRS inv. brems. heating [Mbar/ns]

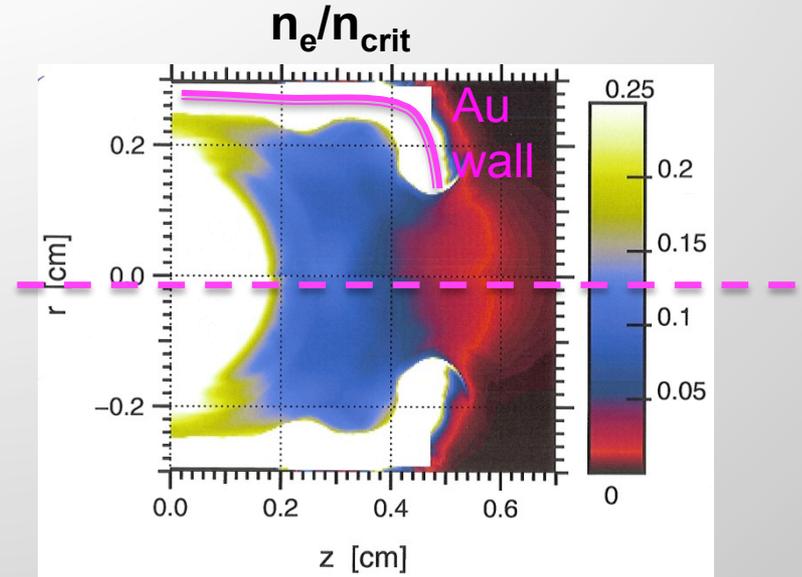
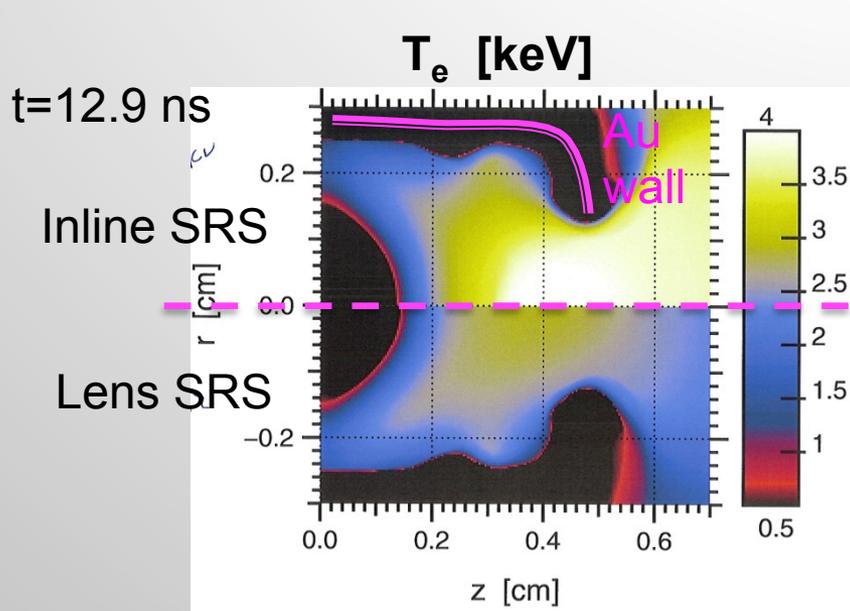


Langmuir wave heating [Mbar/ns]

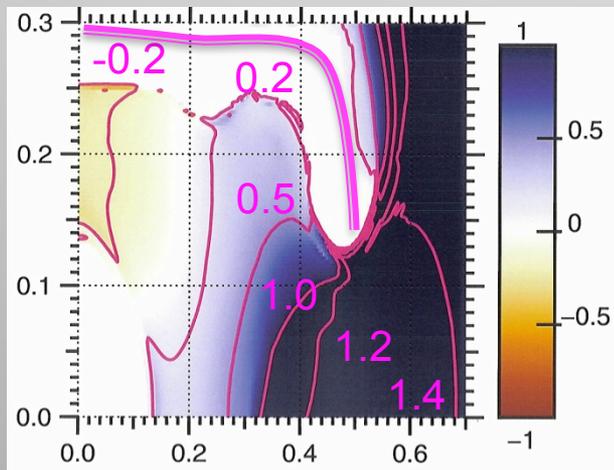


scale 10x
SRS IB

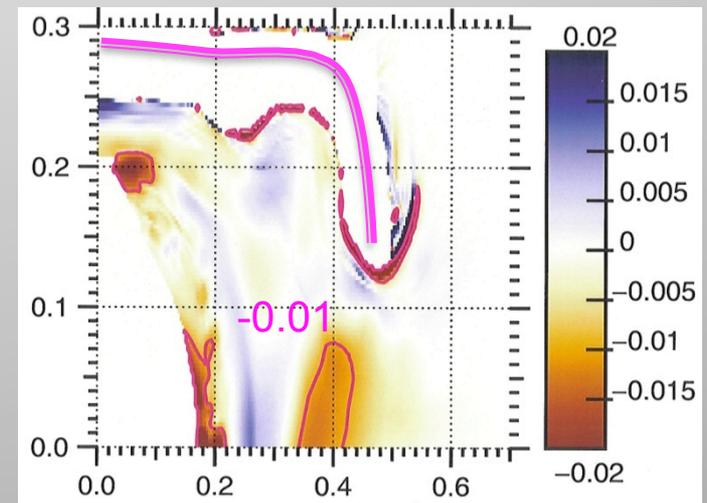
Inline SRS: hotter and less dense LEH than lens SRS



ΔT_e : inline – lens [keV]



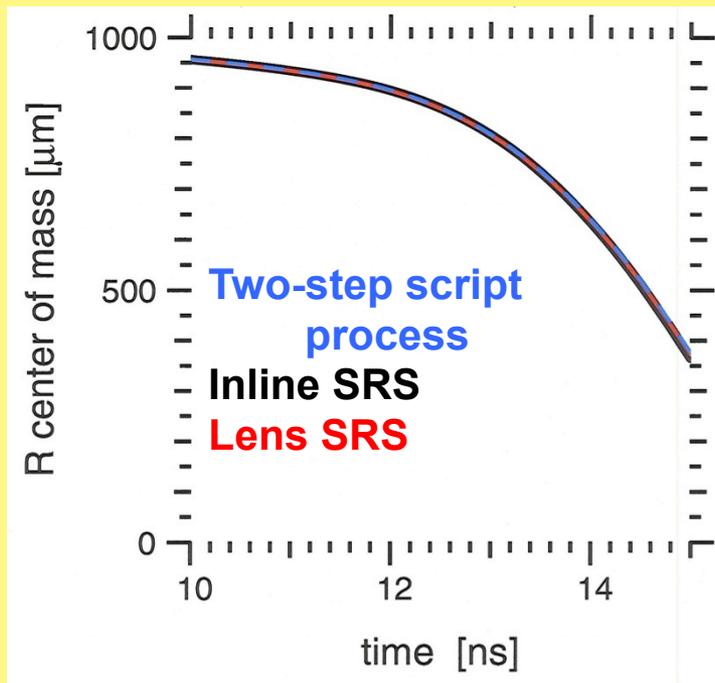
$\Delta n_e/n_{crit}$: inline – lens



Total x-ray drive same for inline and lens SRS, stronger on pole with inline SRS

DRIVE

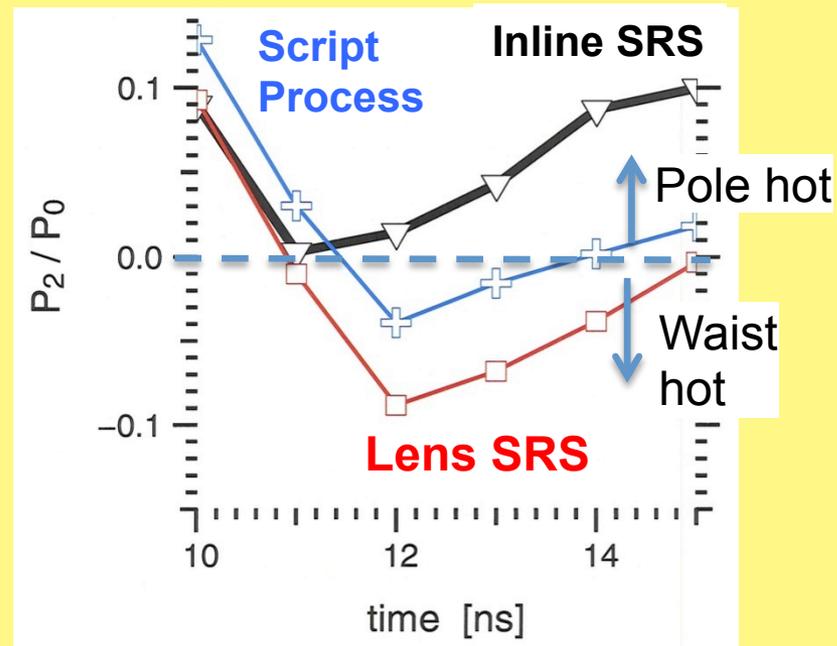
Capsule center of mass:
Total x-ray drive the same



Your eyesight is fine –
3 curves indistinguishable

SHAPE

P_2 moment of x-ray power
deposition at ablation front



$P_2(\text{hot spot}) \sim P_2(\text{x-ray}) * \text{cnvg. ratio}$

Time-integrated:

$P_2(\text{x-ray})/P_0 < 1\%$ for ignition

Conclusions and future work

Inline CBET and SRS in Lasnex:

- Most Langmuir-wave and SRS inverse brems. just inside LEH
- Langmuir-wave heating dominates over SRS inverse brems.

Compared to SRS removed at lens:

- DRIVE: Same total x-ray drive and capsule energetics
- SHAPE: X-ray drive pole-hot with inline SRS – inner beams depleted
 - Closer to experimental data

Future:

- Super-thermal package for hot electrons – local deposition to fluid T_e (shown here) overstates LEH heating
- Replace CBET δn_e clamp with physical nonlinearity:
 - trapping, two-ion wave decay, wave-breaking
- Match capsule shape without dialing clamp

Ultimate goal: predictive model for drive and shape

BACKUP BELOW

Inline CBET model: coupled-mode equations for unpolarized beams: NIF quad-to-quad transfer

Steady state, strong damping limit:

$$\frac{dI_1}{dz} = g^* \min \left[I_0 I_1, a \delta n_{\max} \sqrt{I_0 I_1} \right] \quad g = \text{coupling coeff}$$

$$\frac{dI_0}{dz} = -\frac{\omega_0}{\omega_1} \frac{dI_1}{dz} \quad \text{Manley-Rowe}$$

beams
0 and 1

$$\delta n_e \propto \min \left[\sqrt{I_0 I_1}, \delta n_{\max} \right] \quad \text{Ion wave amplitude, clamp } \delta n_{\max}$$

Ion-wave momentum and heat deposition:

P. Michel et al., PRL 2012

$$m_i \frac{d\langle \vec{v}_i \rangle}{dt} = \alpha \vec{k}$$

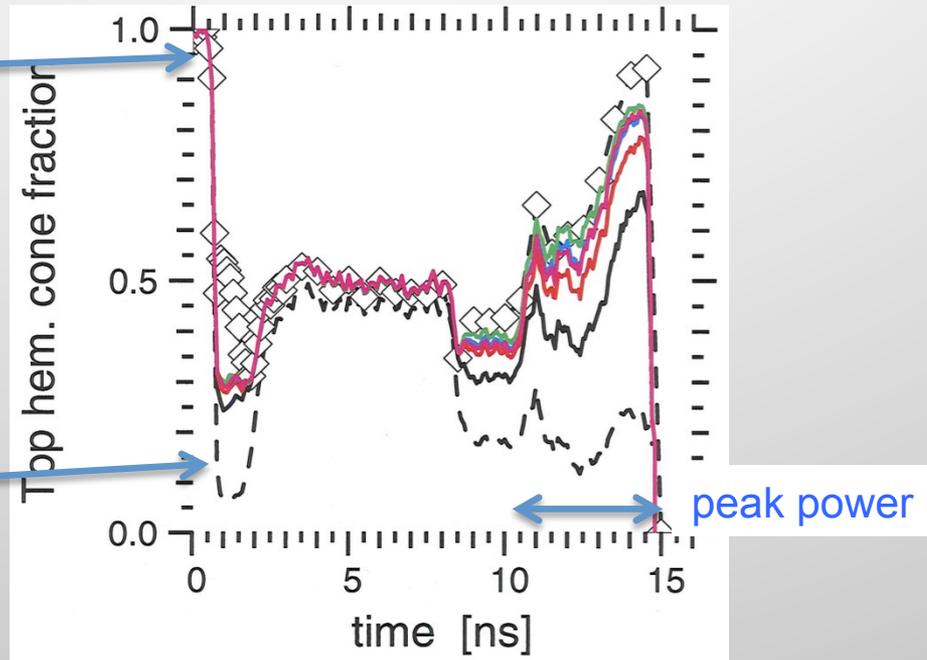
$$\frac{dT_i}{dt} = \frac{2}{3} \left(\omega - \vec{k} \cdot \langle \vec{v}_i \rangle \right) \alpha$$

$$\alpha \equiv \frac{|E_k|^2 \text{Im} \chi_i}{8\pi n_i}$$

Laser cone fraction: N121130

Diamonds: script on 600 ray plasma maps

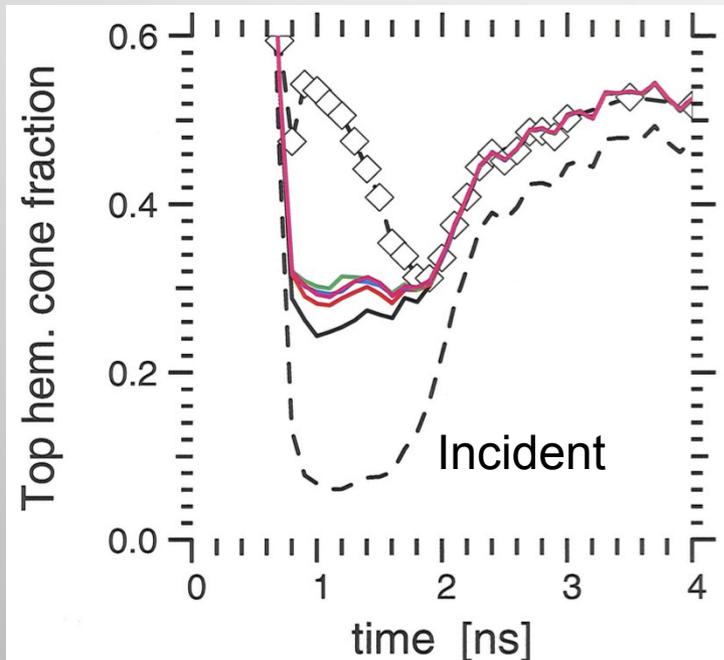
Dashed: incident (BS removed)



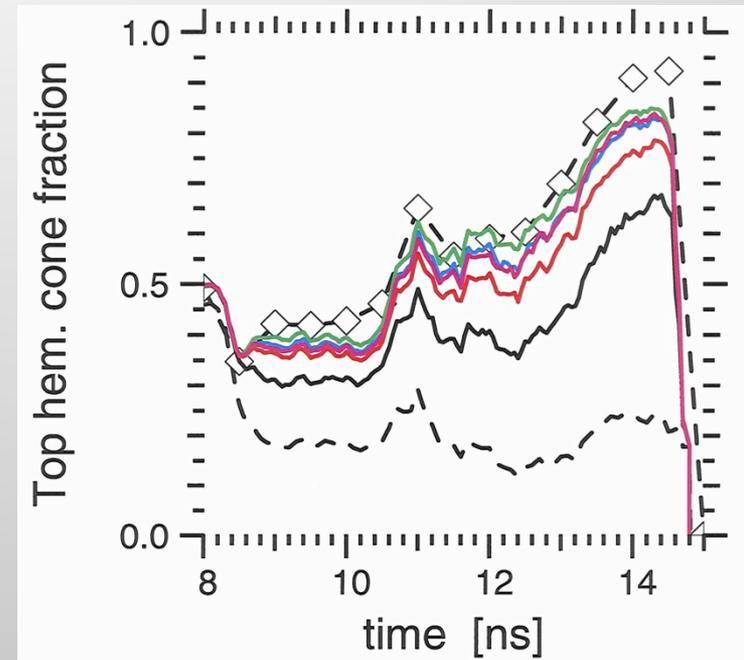
- Rays per quad: 300 (nominal UBT) 600, 900, 900 no pond / heat*, 1200
- No ponderomotive force = momentum deposition by lasers (of any kind, not just CBET), and no CBET ion heating.
 - Enough rays needed to resolve quad intensity on Hydra mesh

Laser cone fraction: picket and peak

Picket: script gives more CBET, neglects inv. brems. absorption

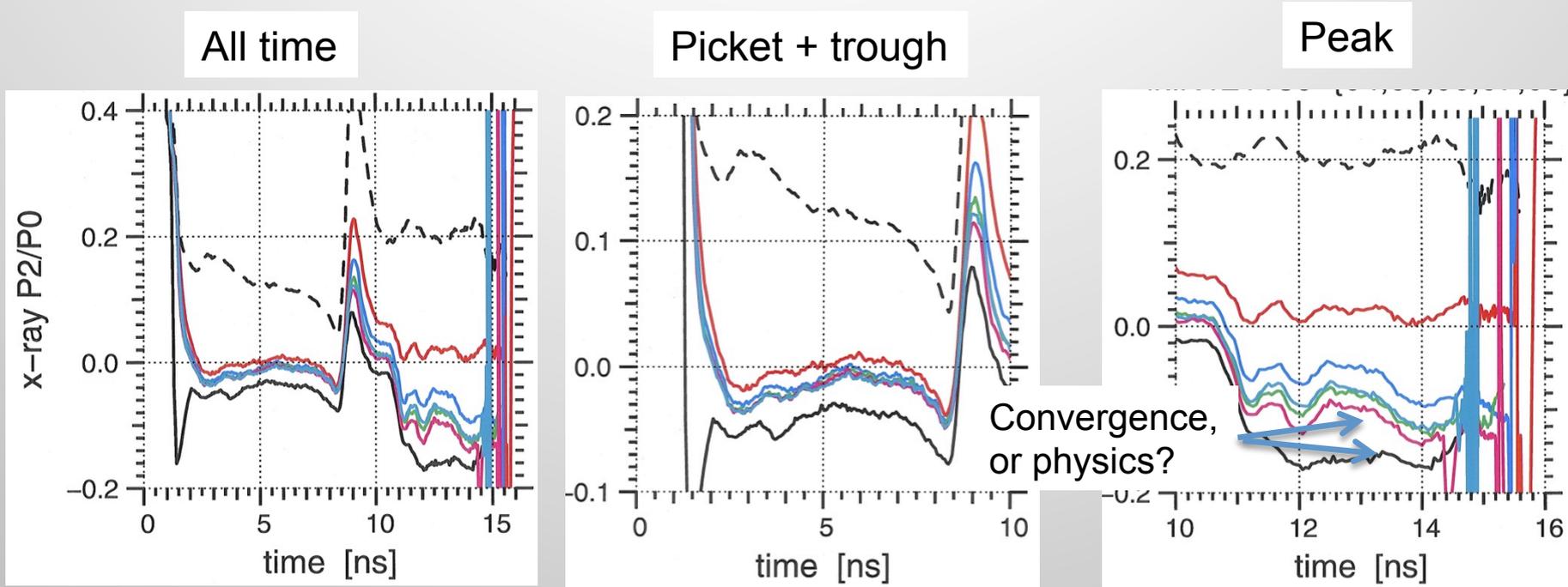


Peak: inline converges to script, with enough rays



- Diamond: script on 600 ray plasma maps
- Rays per quad: 300 (nominal UBT), 600, 900, 900 no pond / heat, 1200

X-ray flux P2 moment at ablation front: script consistently above inline CBET



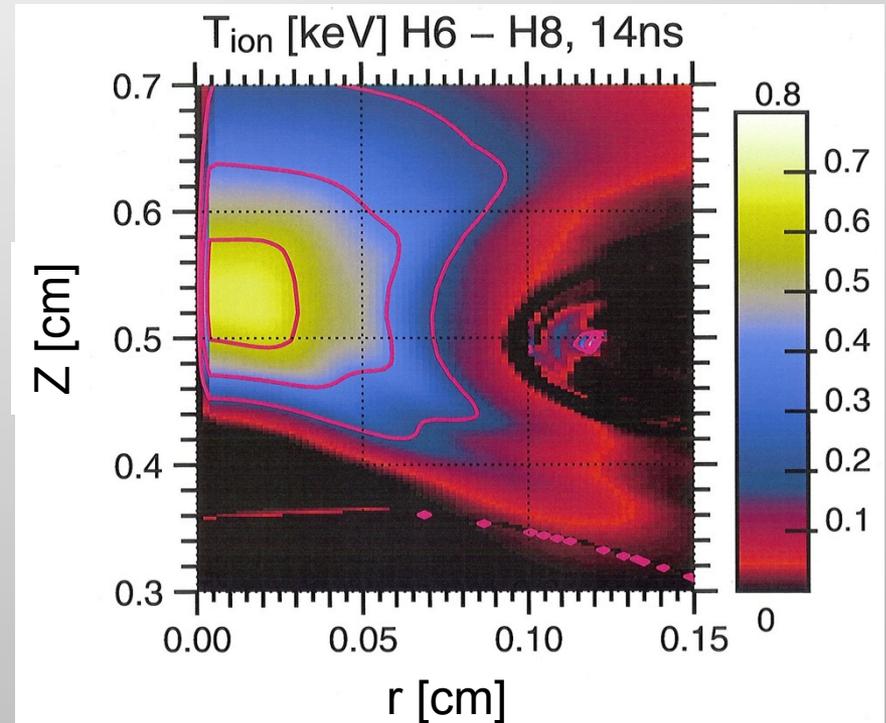
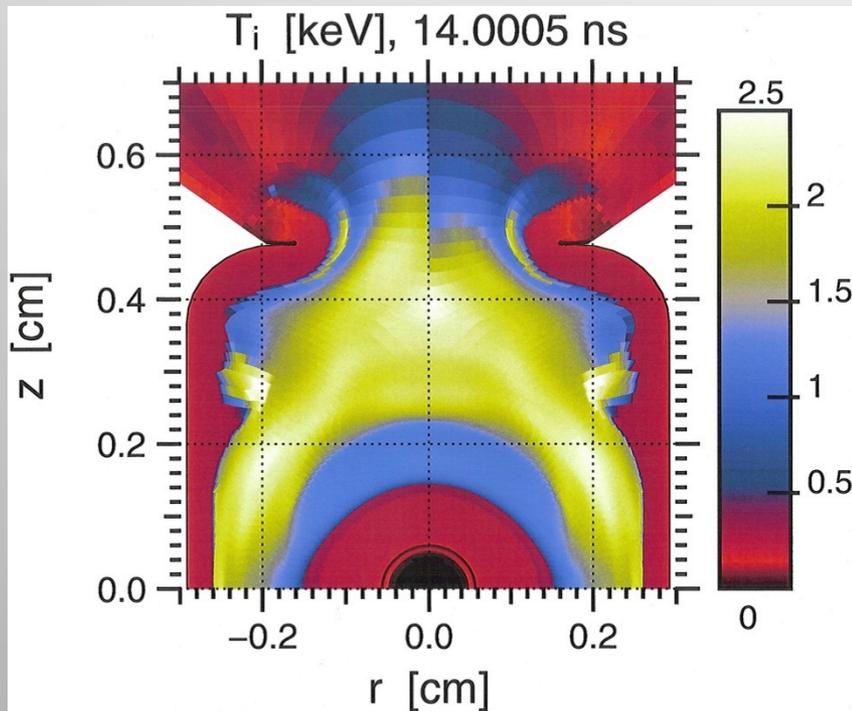
- Black dashed: BS removed at lens, no CBET
- Black solid: two-step process: pre-CBET, script, post-CBET w/ BS removed
- Rays per quad: 300 (nominal UBT), 600, 900, 900 no pond / heat, 1200
- Two 900-ray cases almost the same: ion-wave deposition doesn't affect CBET

Ions hotter in LEH with CBET ion-wave deposition

N121130 at 14.0 ns – end of peak power

Left: Ion heating + pond. Forces
Right: both off

With deposition – without:
Zoom on LEH



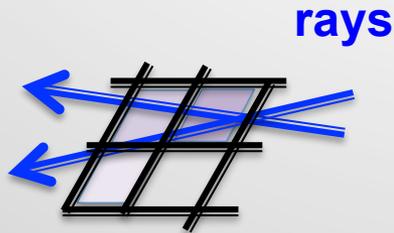
Contours at 200, 400, 600 eV

CBET difference insignificant

CBET model uses zonal intensities to update ray power

Rays carry power, intensity is *zonal* quantity

Intensity
on mesh



CBET ray power change in zone,
unsaturated case:

$$\frac{dI_1}{dz} = gI_0I_1 \quad \rightarrow$$

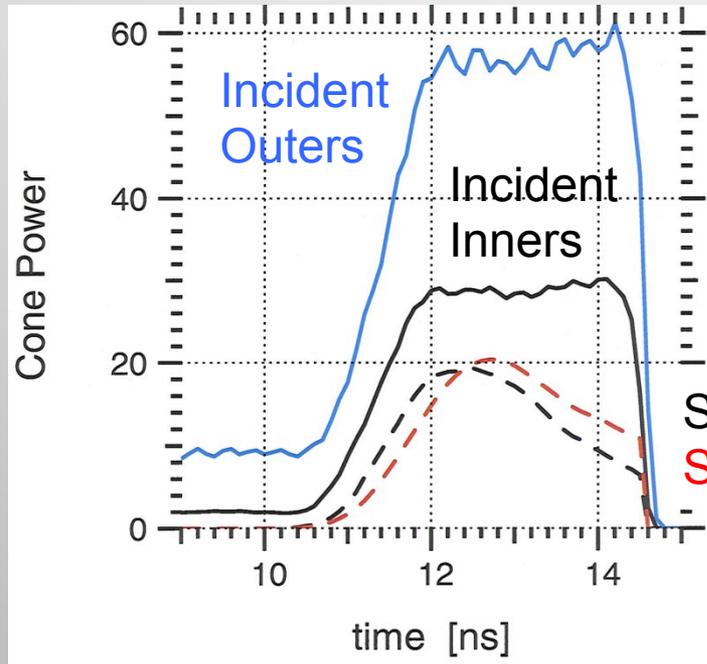
$$P_{ray,1}(\text{end}) = P_{ray,1}(\text{begin}) \exp[gI_0 \Delta z]$$

- Transfer along rays, with zonal intensity
- Enough numerical rays needed to resolve intensity

Inline model: intensities on 3D mesh

- “3D wedge run:” effectively 2D plasma conditions
- Inline model: additional azimuthal coordinate for intensities
- Hohlräume use 2.5° wedge → 144 azimuthal zones
- Each quad has 3D (x,y,z) intensity – need more rays than 2D (r,z) intensity

N121130: Large inner SRS, other backscatter small

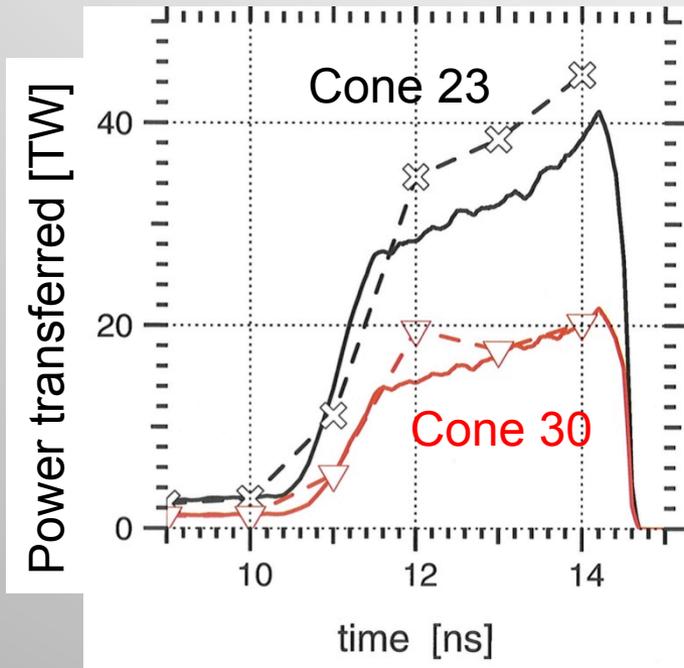


Lens SRS run: much lower incident power to CBET region

SRS 23
SRS 30

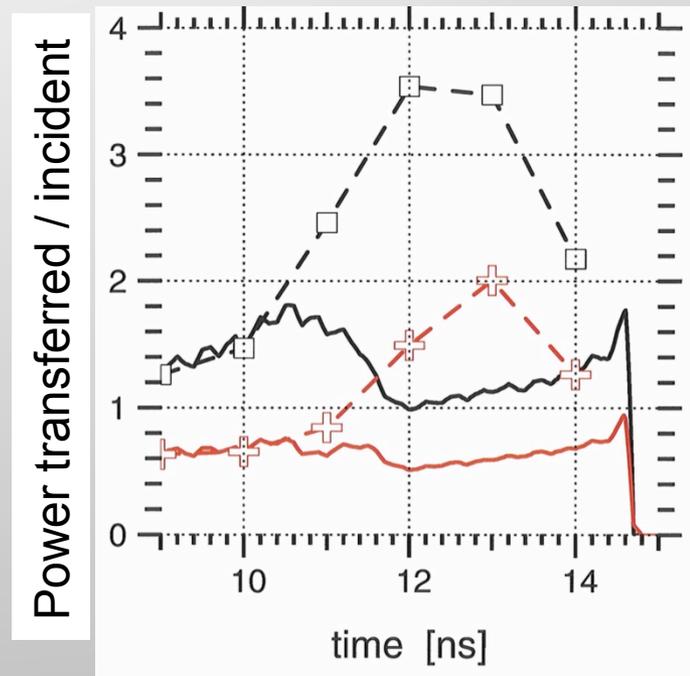
Less CBET to inners with inline SRS – especially relative to incident

Absolute power transferred to inners:
depends on incident power



--- Lens SRS
— Inline SRS

Relative increase in inner power:
depends only on plasma conditions
if no pump depletion



$$\partial_z I_{in} = g I_{in} I_{out}$$

$$\rightarrow I_{in}^{post} = I_{in}^{inc} \exp[g I_{out} L]$$

Outline: Inline Hydra CBET model results on high-foot shot N121130

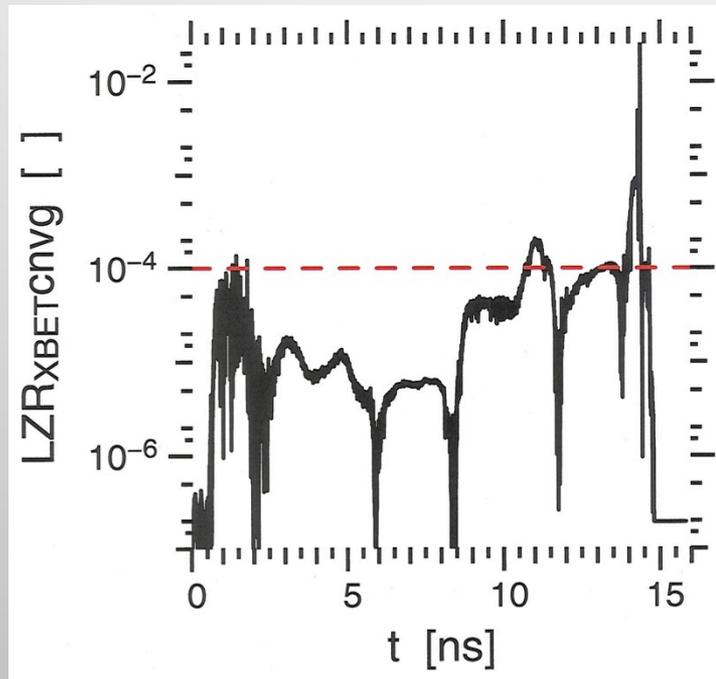
- Model runs with ***NO*** known bugs – hats off to Scott!
- Physics results similar to what we found previously on hi-foot shot N131118 (D. Strozzi, APS-DPP 2014, AX WIP Jan. 2015)
- With saturation clamp $\delta n_e/n = 10^{-3}$, script CBET \geq inline model
 - Picket: inline gives less CBET than script, which neglects inv. brem.
 - Peak power: inline converging toward script, with enough numerical rays
 - Inline ion-wave momentum and heat deposition makes LEH ions hotter, has little effect on CBET
- All inline runs had measured backscatter removed at lens
 - Inline SRS needed to consistently handle backscatter – in the works

Inline Hydra runs for N121130

- Laser power: Measured backscatter removed at lens, no drive multipliers
 - Purpose is to study inline CBET model, and compare with script
 - Not a consistent post-shot simulation – requires inline SRS package
- Two-sided (+ and – z): inline CBET ***CAN NOT*** be run with z-symmetry plane! E.g. no one-sided hohlraum runs.
- CBET saturation clamp $\delta n/n = 10^{-3}$: larger than what is needed for script to agree with shape data during peak power
- Other CBET settings:
 - LZR_XBET_klocal = 1: use intensity-weighted k-vector in each zone
 - LZR_XBET_align = 0: should not be used with klocal
 - LZR_XBET_istate = 1: use post-CBET intensity as initial guess for next cycle
 - LZR_XBET_iter_lite = 2: save coupling data in all active zones after 2 iterations
 - LZR_XBET_cnvg_tol = 1E-4: iterate til fractional power lost due to CBET is below this
 - LZR_XBET_niter_mx = 10: max. allowed iterations
 - ray_power_flr = 1E-4: remove rays when they reach this fraction of initial power
 - bm_reseed = 1: roll dice for rays every cycle

Numerical error in CBET package is almost always below requested 10^{-4}

$LZR_XBET_cnvg = \text{power error in CBET package} / \text{incident power}$



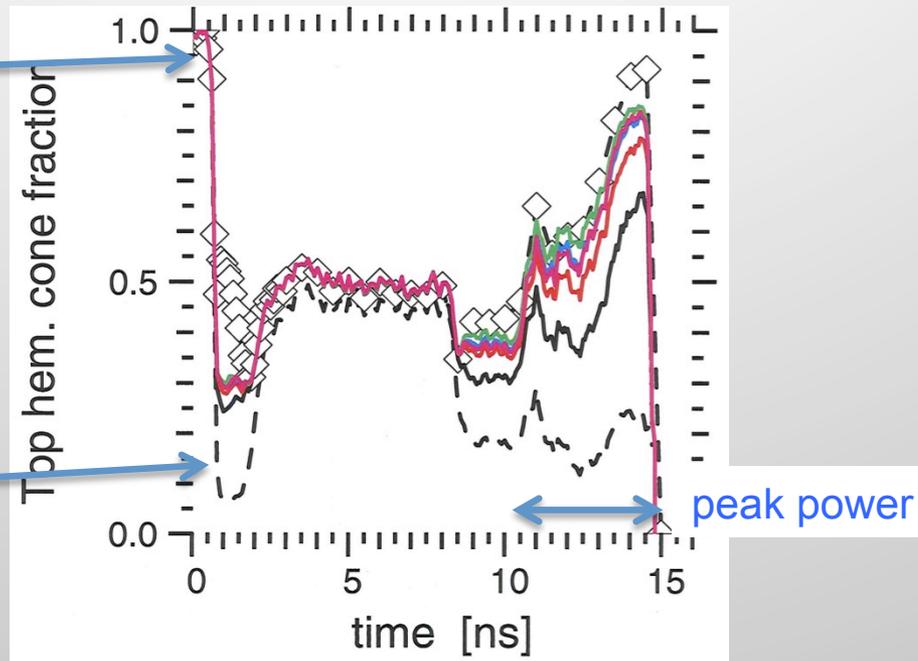
$LZR_XBET_cnvg_tol = 10^{-4}$
Requested tolerance

- CBT package does not exactly satisfy Manley-Rowe, i.e. net energy lost by lasers should be energy into ion waves, but isn't
- Other errors in laser package generally larger than CBET error

Laser cone fraction: N121130, top hemisphere

Diamonds: script on 600 ray plasma maps

Dashed: incident (BS removed)

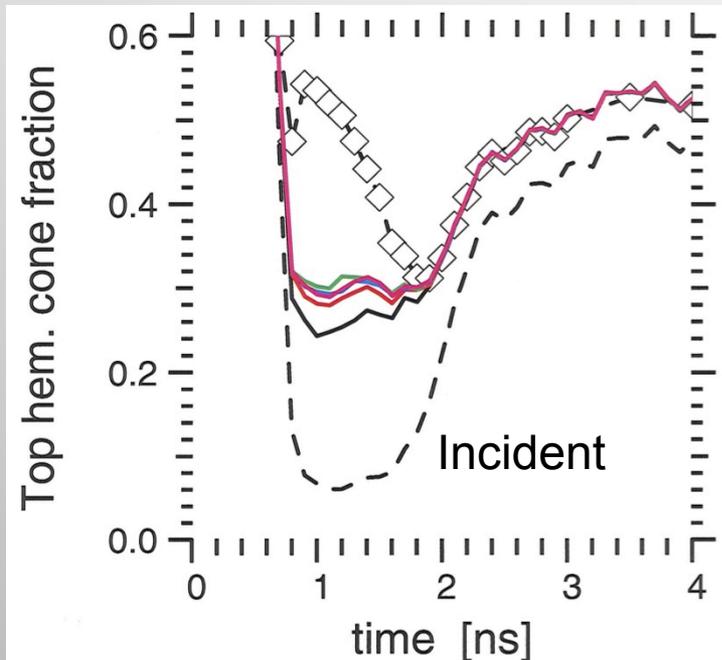


Rays per quad: 300 (nominal UBT) 600, 900, 900 no pond / heat*, 1200

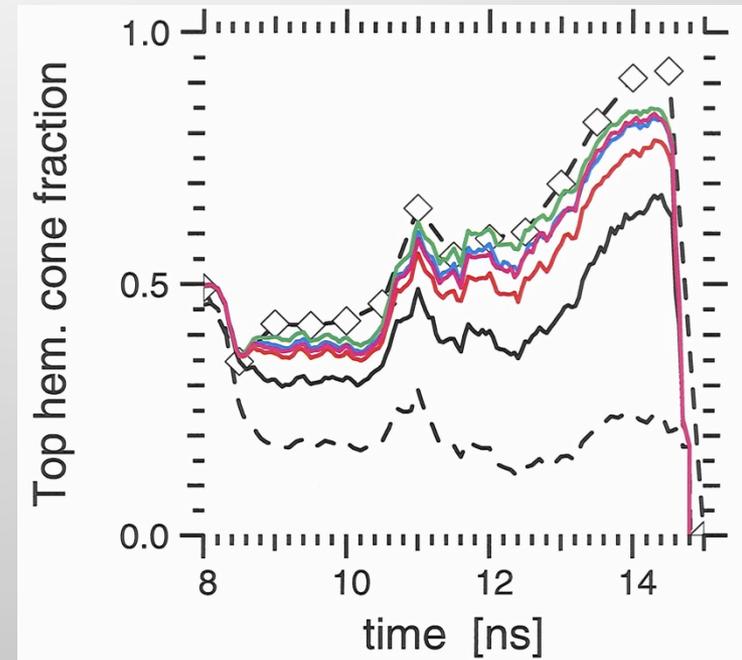
- No ponderomotive force = momentum deposition by lasers (of any kind, not just CBET), and no CBET ion heating.
- Enough rays needed to resolve quad intensity on Hydra mesh
- Different rays on inners and outers may reduce total number

Laser cone fraction: picket and peak

Picket: script gives more CBET, neglects inv. brems. absorption



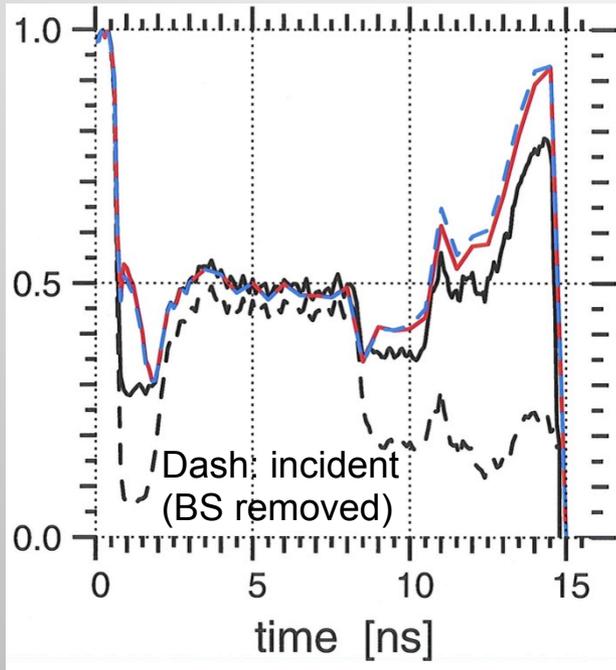
Peak: inline converges to script, with enough rays



- Diamond: script on 600 ray plasma maps
- Rays per quad: 300 (nominal UBT), 600, 900, 900 no pond / heat, 1200

Laser cone fraction: CBET has little effect on script calculation of CBET: no need to iterate

Top hem. cone fraction

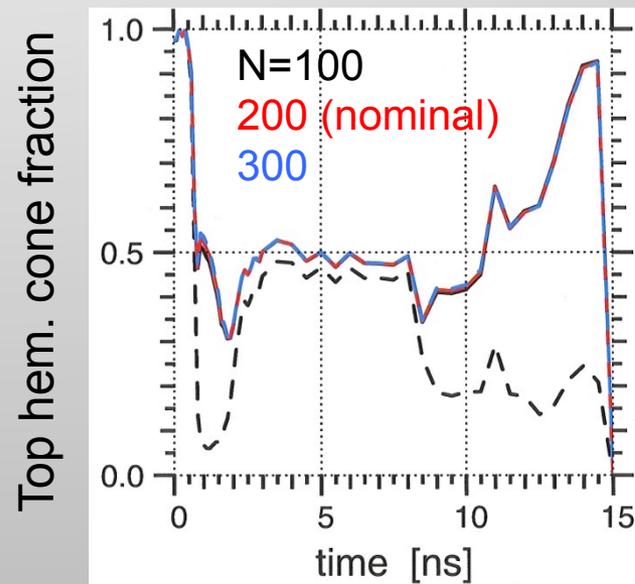


Script on no-CBET plasma maps

Script on inline 600-ray plasma maps

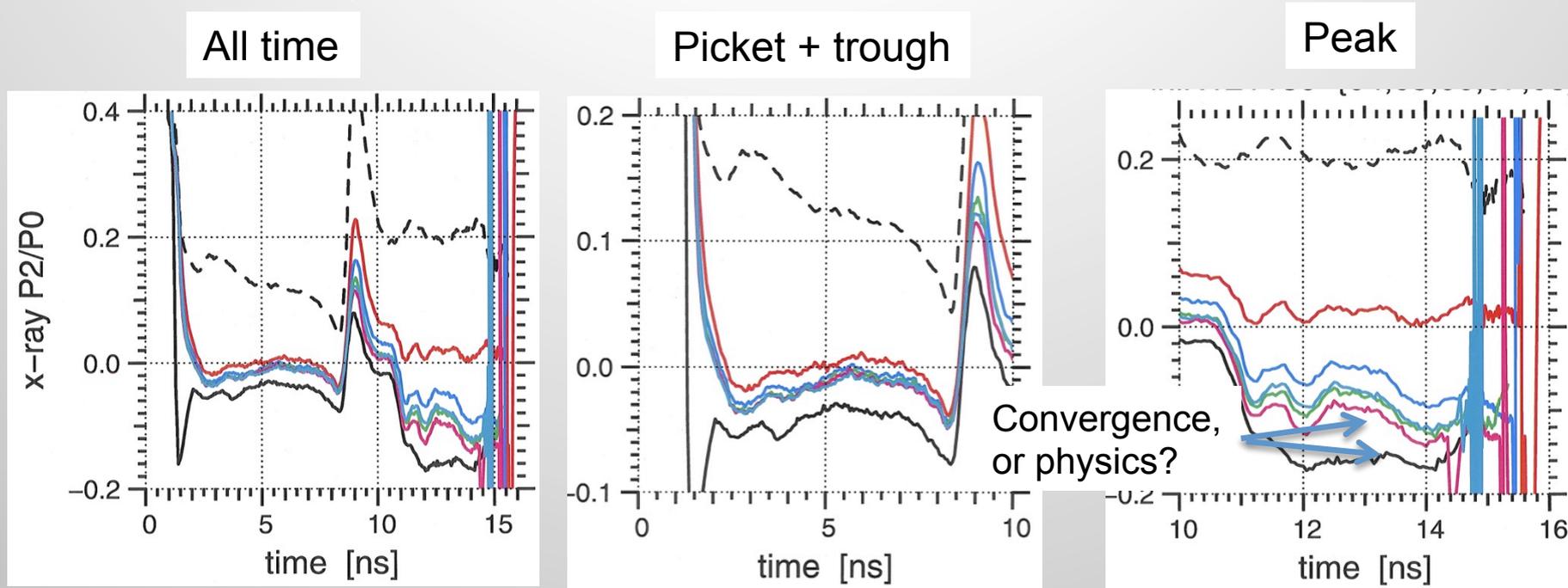
Inline, 600 rays (1200 rays approaches script)

Script converged for
 $N := N_x = N_y = N_z = 100$



Yes, there really are 3 curves. Your eyesight is fine.

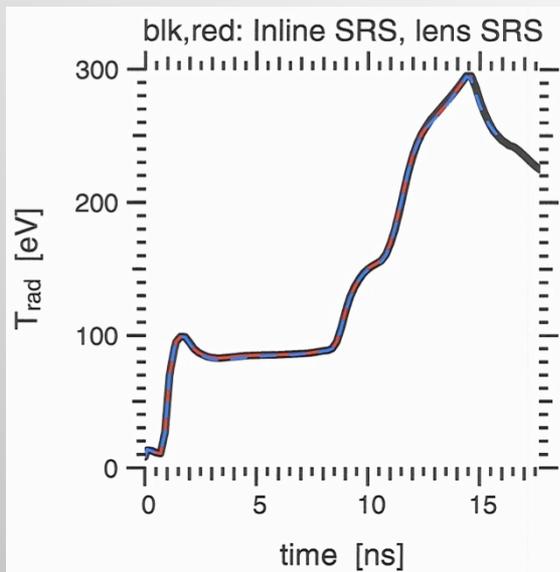
X-ray flux P2 moment at ablation front: script consistently above inline CBET



- Black dashed: BS removed at lens, no CBET
- Black solid: two-step process: pre-CBET, script, post-CBET w/ BS removed
- Rays per quad: 300 (nominal UBT), 600, 900, 900 no pond / heat, 1200
- Two 900-ray cases almost the same: ion-wave deposition doesn't affect CBET
- 900 rays looks adequate to end of trough, 1200 may not be enough for peak

Inline vs. lens SRS: total x-ray drive same, stronger on pole with inline

T_{rad}



Script two-step

